GEOLOGICAL CIRCULAR **75-5**

Flood Hazards along the Balcones Escarpment in Central Texas

Alternative Approaches to their Recognition, Mapping, and Management

BY
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Identification of Cover Photo:

Oblique satellite photograph of the Balcones Escarpment between the Nueces River (lower left) and San Antonio (top center). The bright response of river channels on the Edwards Plateau results from reflection off coarse, white limestone sediment transported by recent floods. (NASA Skylab 4 S-190A Frame 52-014, 29/11/73.)

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FLOOD HAZARDS ALONG THE BALCONES ESCARPMENT IN CENTRAL TEXAS
Alternative Approaches to their Recognition, Mapping, and Management

Victor R. Baker[1]

INTRODUCTION

The public tends to dismiss floods as somewhat unreal catastrophes or occasional inconveniences that usually affect others. When a flood disaster strikes at the local level, the magnitude of the event is appraised in terms of the damage to human works on the river-valley floor or, in some cases, in terms of the loss of life. Resources are mobilized to combat the disaster, and discussions ensue concerning flood control plans and projects. The affected communities may then learn that they have experienced a "100-year flood," or a flood discharge that has a "1 percent probability of being equalled or exceeded in a given year." They may further learn that the unpleasantness of this event can be prevented and controlled by various combinations of levees, dikes, dams, reservoirs, and channels. Rarely does the public hear that floods are a natural part of a river's activity, really an essential part of a river's long-term task of conveying water and sediment down gradient from an evolving landscape to a base level, such as the Gulf of Mexico. Flooding is a great natural hazard because people occupy river-valley bottoms, flood plains, and other flood-prone areas.

The term "flood" is variously defined depending on the concerns of its user. To all, it is an overflow of a stream channel that exceeds certain limits. To the flood-plain manager, these limits are those at which life and property are damaged or threatened. To the hydrologist, the limits are arbitrarily defined on the basis of magnitude-frequency studies of streamflow. The geomorphologist and the geologist view floods relative to the natural features associated with the stream or river. Clearly, the study of floods and the mapping of their potential occurrence require an interdisciplinary approach. The accelerating demand for flood-plain information makes desirable an evaluation of alternative techniques to standard engineering flood line and regional flood analyses (Wolman, 1971). Different mapping techniques may be appropriate to different localities depending on the local hydrologic regime, the level at which planning is being performed, and the funds available to finance the study. A geologic approach to flood hazard mapping can be used effectively at the state or regional scale to provide interim flood hazard information prior to detailed hydrologic and hydraulic studies on a local basis. If included within an overall program of regional environmental geological mapping, morphological flood-plain mapping can provide a relatively inexpensive byproduct of a general program of environmental inventory.

It is a well-known fact that, despite immense public expenditures for flood protection, flood losses remain substantial, potentially costing an average of $2 billion (1966 dollars) per year nationally (U. S. Water Resources Council, 1968). Assuming established trends in the increased use and development of hazardous flood plains, this figure will increase to $5 billion by 2020. In 1966 the estimated annual flood damage for Texas rivers draining more than 250,000 acres, exclusive of the Rio Grande, was $28.2 million (U. S. Water Resources Council, 1968). Total damage to smaller basins was estimated at $55.9 million. Despite the current total investment of over $400 million in flood control works, the total damage figures are projected to rise to $59.3 and $125.3 million respectively by the year 2000. An increasing percentage of the annual national flood loss is the result of so-called catastrophic floods (Holmes, 1961), i.e., floods which either (1) have a return period of 100 years or more, or (2) cause failure of a flood protection project by exceeding the project design flood. The average amount of flood loss from floods of moderate frequency is decreasing relative to these catastrophic events. The estimated $3 billion damage produced by Hurricane Agnes flooding in the eastern United States during the summer of 1972 may represent the pattern for most future flood losses. Approximately 40 percent of the damage from Agnes flooding occurred in areas which had received federally funded flood protection benefits. The message for Texas, where flooding occurs because of what is perhaps the most catastrophic rainfall regime in the conterminous United States, is that flood-plain managers must consider alternative approaches to reservoirs, levees, floodwalls, and channels. Flood-plain management requires that an all-out effort be made to (1) increase basic knowledge of floods and flood hazards, (2) define and outline major flood areas, and (3) improve methods of flood-frequency analysis (U. S. Congress, 1966, p. 18-19).

White (1964) has shown that from the theoretically broad range of choice for the flood-plain manager, only a few choices are generally considered in decision-making. This results in far less efficiency than could be achieved by

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considering the whole range of possible choices. Two main factors seem to limit choice: the flood-plain manager's perception of the nature and magnitude of the flood problem, and his perception of alternative responses. This report is a preliminary attempt to describe the flood problems of Central Texas, to suggest alternative approaches to their evaluation, and to relate these scientific goals to the managerial goals of the State and of local communities.

Many individuals and organizations provided information that aided in the preparation of this report. H. N. McGill and A. B. Colwick, Soil Conservation Service, and E. V. Diniz, Texas Water Development Board, provided information on the 1972 New Braunfels flood. James Bohn and E. E. Schroeder provided information on U. S. Geological Survey programs of flood hazard evaluation and flood-plain mapping. P. C. Patton assisted with reduction of regional hydrologic data and field investigations of geomorphic flood effects. R. W. Lester and P. A. Smith assisted with studies of botanic methods of flood-plain mapping. The report benefited from reviews by W. L. Fisher, T. C. Gustavson, R. A. Morton, and E. G. Wermund, Bureau of Economic Geology, The University of Texas at Austin. Financial support for the study was provided by the Bureau of Economic Geology.

FLOODS IN CENTRAL TEXAS

Climate and physiography are the controlling factors of the chronic floods that plague Central Texas. The dominant physiographic element of the region is the Balcones Escarpment (fig. 1) which separates the deeply dissected limestone terrain of the Edwards Plateau from the gently sloping, undulating clay and sand terrain of the Coastal Plain. Mean annual precipitation along the escarpment varies from 32.58 inches at Austin to 22.0 inches at Brackettville (U. S. Army Corps of Engineers, 1964). Close spacing of isohyets at the escarpment (Carr, 1967, fig. 2) shows the effect of this topographic rise. Studies of average monthly precipitation (Carr, 1967) show that maxima occur in May and September with lows in winter and summer. The maxima result from convective thunderstorm activity and the movement of moisture-laden air along the established tropical Gulf storm tract. These storms have

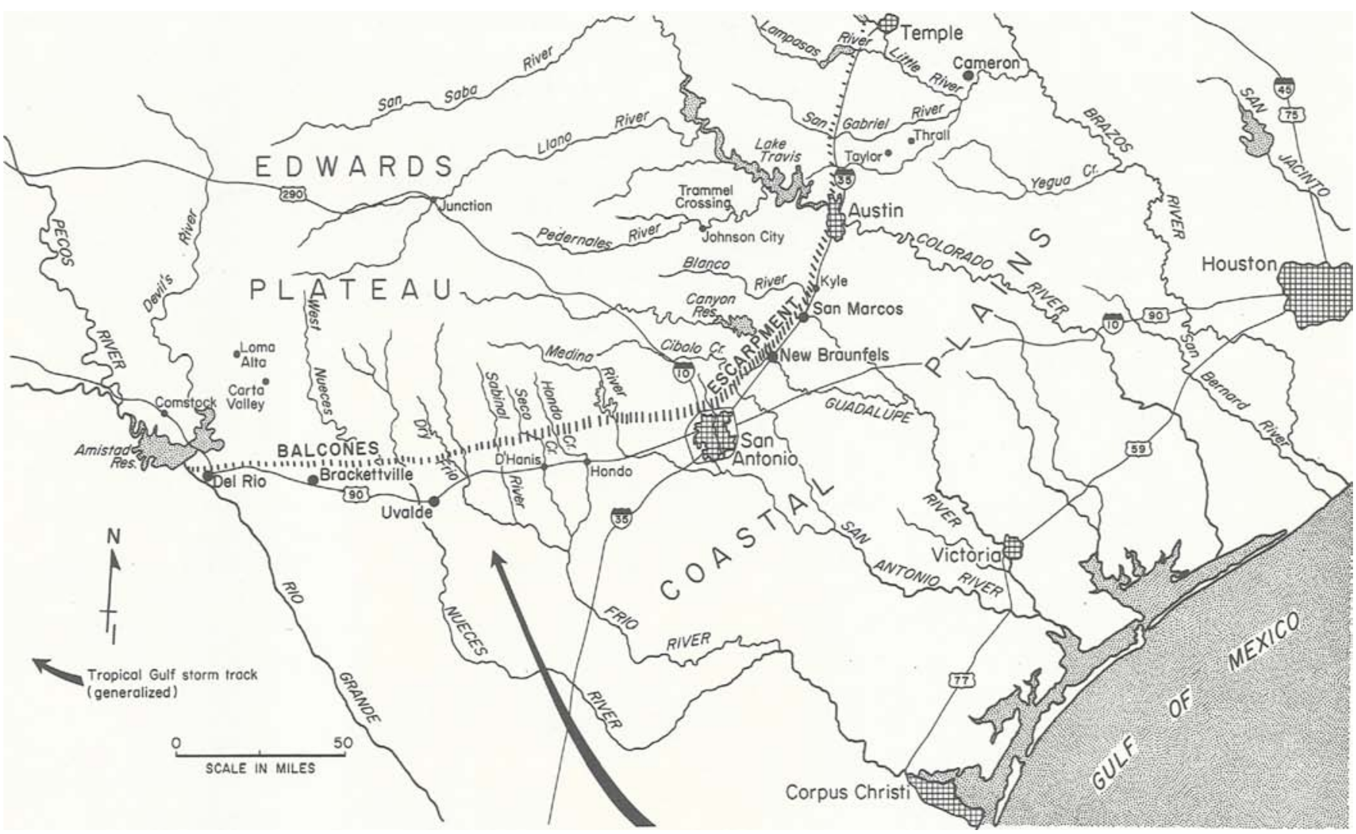

Figure 1. Physiographic elements of Central Texas.

produced some astonishing amounts of rainfall, including both national and world records for a given duration (fig. 2).

The western end of the Balcones fault zone is characterized by a relatively steep, high escarpment at right angles to the general direction of storm winds. The situation is ideal for lift-convective storms as described by Dorroh (1946, p. 6), who states, "... at or near sudden changes in topography the characteristic rainfall intensities will far exceed those normally experienced in the vicinity." The most violent form of atmospheric convection is the thunderstorm, which results when thermal instability occurs in lifting air along topographic rises, fronts, and isobaric convergence. One of the most spectacular cloudburst-type thunderstorms on record occurred on May 31, 1935, when a tongue of moist air protruded from the Gulf of Mexico to the vicinity of D'Hanis, Texas (Morgan, 1966). The lift effect of this convectively unstable air at the Balcones Escarpment resulted in the production of 22 inches of rainfall in 2 hours 45 minutes.

Weather disturbances of tropical origin are responsible for the greatest flood-producing storms which affect Texas. The meteorology of such storms is characterized by easterly waves which pick up enormous quantities of moisture from passage over thousands of kilometers of warm tropical seas (Orton, 1966). Weather conditions in the Caribbean make stable easterly waves most likely to occur in the month of September. If an especially vigorous wave reaches the orographic barrier of the Balcones Escarpment, long-duration, heavy rains may result. This happened in the great Thrall, Texas, storm of September 9-10, 1921, which yielded locally 36.4 inches in 18 hours and 38.2 inches in 24 hours. This storm was considered to be the greatest of all continental United States rainstorms. Another example is the storm of September 9-10, 1952, which came about from the near simultaneous arrival over Texas of a pressure surge from the northeast and the easterly wave trough. The warm easterly tropical air current decreased in stability from lifting over the Balcones Escarpment and ascended rain-cooled air that developed over the dissected Edwards Plateau terrain (Orton, 1966). Storm totals of 20 to 26 inches were concentrated in small centers over the upper Pedernales and Guadalupe Rivers, with the most intense cell located between Stonewall and Johnson City (Lott, 1952). The peak stage at the Johnson City bridge over the Pedernales was recorded as 48 feet by local residents. The peak discharge at that location was determined to be 441,000 cfs (Breeding and Montgomery, 1954). For smaller streams in the Guadalupe basin, water depths up to 60 feet and flow velocities exceeding 20 fps were recorded. If the advancing flood wave had not been stopped by Mansfield Dam, it is estimated that the flood stage at Austin would have been 47 feet (750,000 cfs), exceeding all flows since at least 1833 (Orton, 1966).

When easterly waves become unstable and a vortex results, the phenomenon of cyclonic action may intensify to create a hurricane. If hurricanes of both Atlantic and Gulf of Mexico origin move inland to become extratropical, they may produce very heavy rainfall and extensive flooding (Carr, 1966). Frequently hurricanes of minor intensity relative to their wind or tide damage potential become major rain producers after becoming extratropical. In 1954, Hurricane Alice entered Mexico 85 miles south of Brownsville and traveled up the Rio Grande to the lower Pecos and Devil's River watersheds. The flow at the mouth of the Pecos was almost one million cfs, nearly eight times any previous flow during a long record (Myers, 1966).

The meteorologic factors that affect the magnitude and intensity of precipitation are the key to forecasting the temporal occurrence of floods. However, once precipitation reaches the ground, the conversion to flow in a river channel depends mainly on the physical characteristics of the drainage basins and stream channels (Rodda, 1969). Very rapid runoff in the Edwards Plateau is promoted by sparse scrub vegetation, thin lithosols, and bare limestone slopes that are often clay sealed (Tinkler, 1971). Steep slopes are common in the headwaters of the major rivers that dissect the plateau. Drainage density measured from 1:24,000-scale topographic maps averages 10 mi/mi^2. Even more significant in concentrating overland flow are the numerous surface rills on hillslopes. Detailed photointerpretation of the Bee Creek drainage basin (3.25 mi^2) near Austin revealed about 1,000 rills.

The geomorphic features of the Edwards Plateau have resulted in a number of distinct flood environments (fig. 3). Immediately upstream from the Balcones Escarpment, the major rivers flow through steep-sided, narrow canyons excavated from the Edwards Limestone and underlying Glen Rose Formation. Along these constricted reaches, high discharges produce relatively great flow depths. Flood stages of 40 to 50 feet are not uncommon along such sections. Upstream from the zone of Balcones faulting, the terrain is dominantly developed on the easily eroded marl and limestone beds of the upper Glen Rose Formation (Wermund, 1974; Morton, 1974). Broad flood plains and terraces are extensively developed in this region, particularly along the Guadalupe, Medina, Sabinal, and Nueces Rivers. Downstream from the Balcones Escarpment, extensive bottomland flood plains are developed in the sand and clay terrain of the Coastal Plain. Rainstorms on the plateau surface result in extensive inundation in such areas. Terraces and broad alluvial surfaces occur above the Coastal Plain river bottomlands and are removed from the flood hazard.

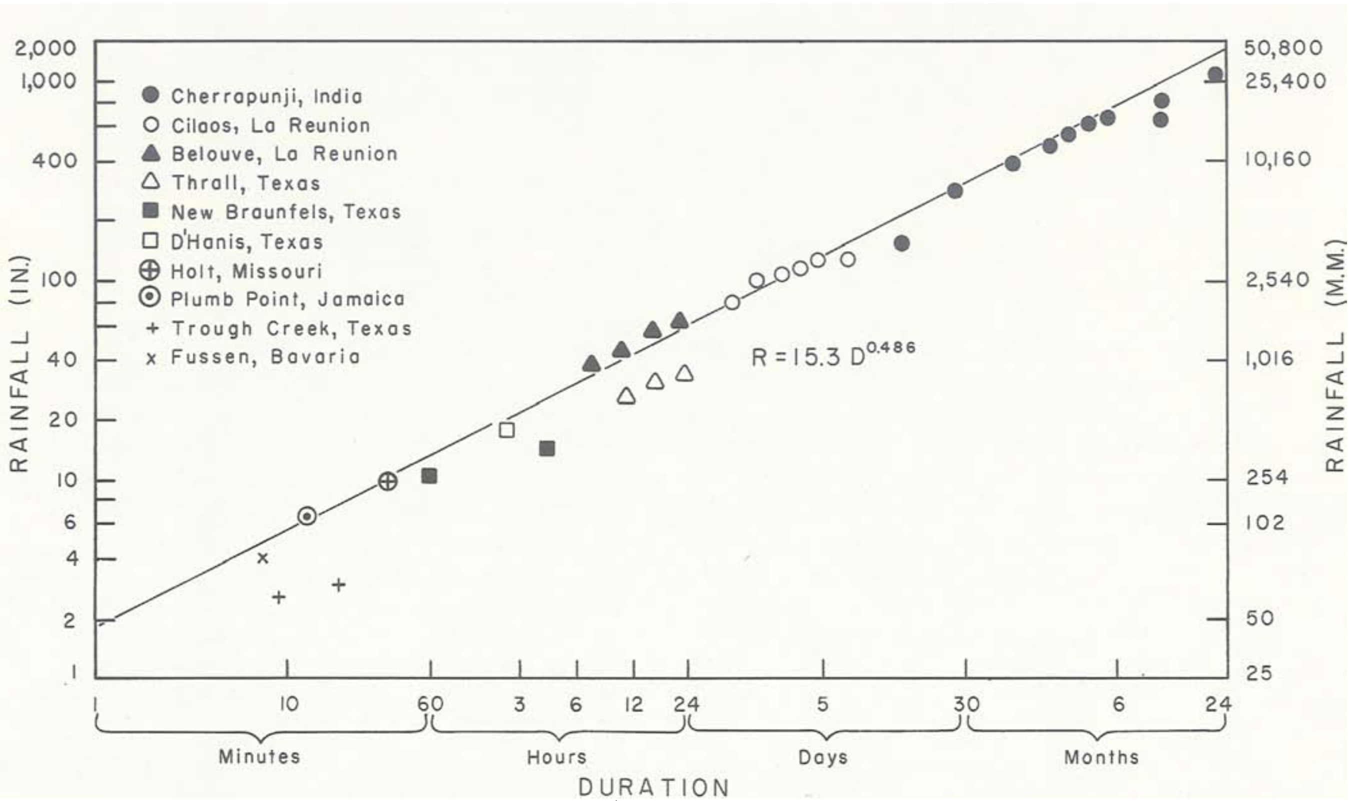

Figure 2. Magnitude-duration relationships for the largest rainfalls of the world and of Texas. World data from Jennings (1950) and Paulhus (1965). Values for the New Braunfels storm (May 11, 1973) reported by Colwick and others (1973).

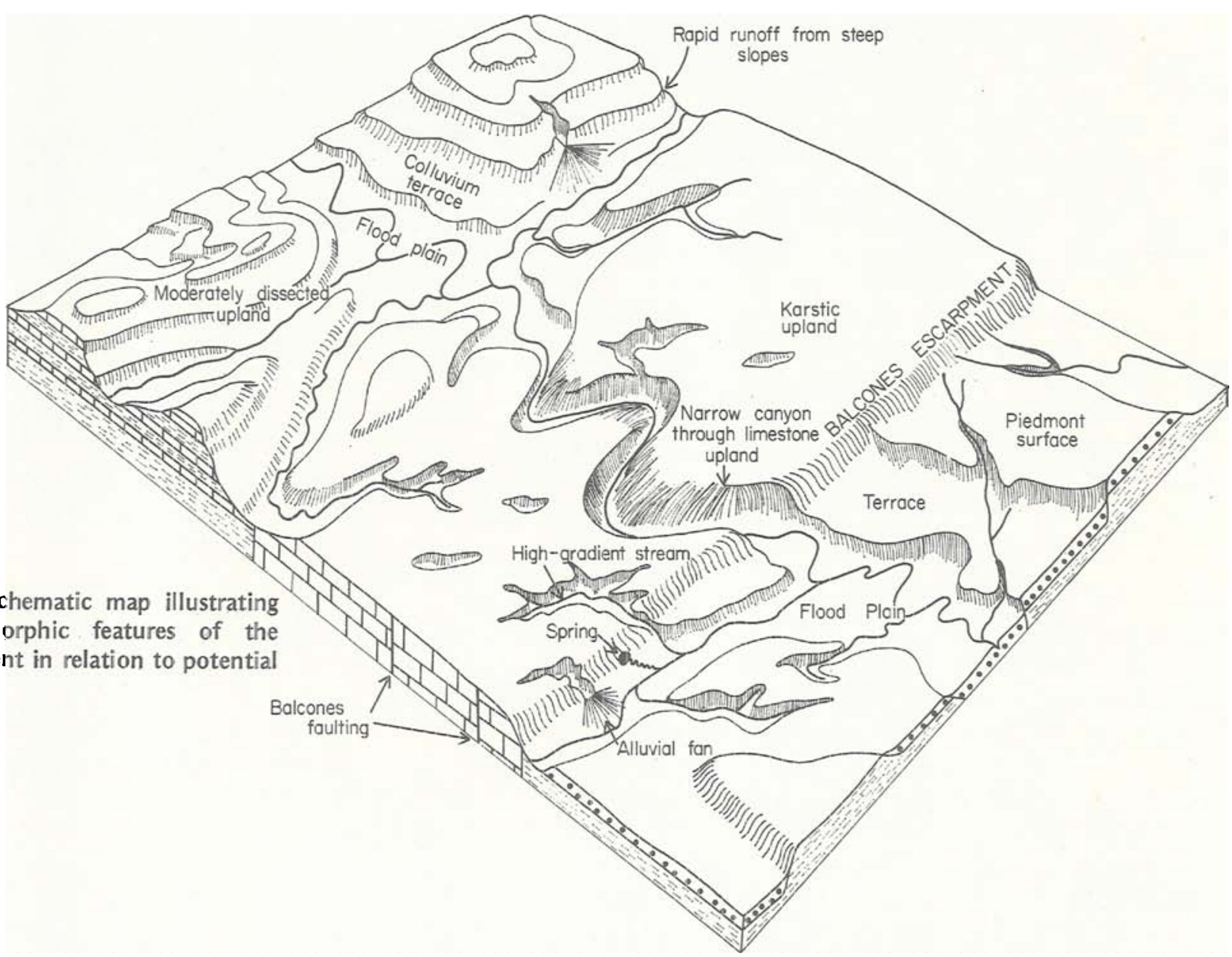

Figure 3. Schematic map illustrating the major geomorphic features of the Balcones escarpment in relation to potential flood hazards.

The flood-peak discharges that result from the meteorologic and physiographic circumstances in Central Texas are well known for their tendency to exceed those recorded from similar-sized drainage basins elsewhere in the United States (Hoyt and Langbein, 1955; Leopold and others, 1964). By examining the relationship between the magnitude of flood discharge and the contributive drainage basin area, it is possible to define an envelope curve for the greatest floods in the region (fig. 4). Many of the flood peaks that define this relationship arose from the individual storms discussed earlier.

The frequency of flood events is perhaps their most misunderstood attribute. Occupants of flood plains are usually unconcerned with major, infrequent floods if one has not occurred within the memory span of older residents (Kates, 1962). However, a rare flood of immense magnitude leaves a much more profound impression than more frequent minor floods. Flood-frequency analysis (Dalrymple, 1960) begins by calculating a relatively simple statistic,

$$\text{Recurrence Interval} = \frac{N+1}{m}$$

where N is the number of years of record and m is the order number of annual peaks, assigning 1 to the largest event, 2 to the next largest, etc. The data are plotted on various kinds of graph paper (fig. 5) with time scales based on statistical theories of extreme values (Gumbel, 1958).

The concept of recurrence interval or "return period" is most difficult for the layman. He might for instance be told that the 441,000 cfs recorded at Johnson City on September 11, 1952, can be assigned a return period of 100 years by extrapolation of the existing gage record (fig. 5A). Statistically, this means that there is a 63-percent chance of getting one or more similar or larger floods in 100 years, a 39-percent chance in 50 years, a 9.6-percent chance in 10 years, and a 1-percent chance in 1 year (Reich, 1973). Another problem is that the common practice of extrapolating flood-frequency curves along the time axis in order to estimate less probable flood peaks can result in immense error. This is especially true in a region where precipitation is highly variable in time and space. Commons (1966) pointed out that streamflow records of even 30 years are practically useless in predicting low-probability floods in Texas. Myers (1969) used a Texas example (fig. 5B) to

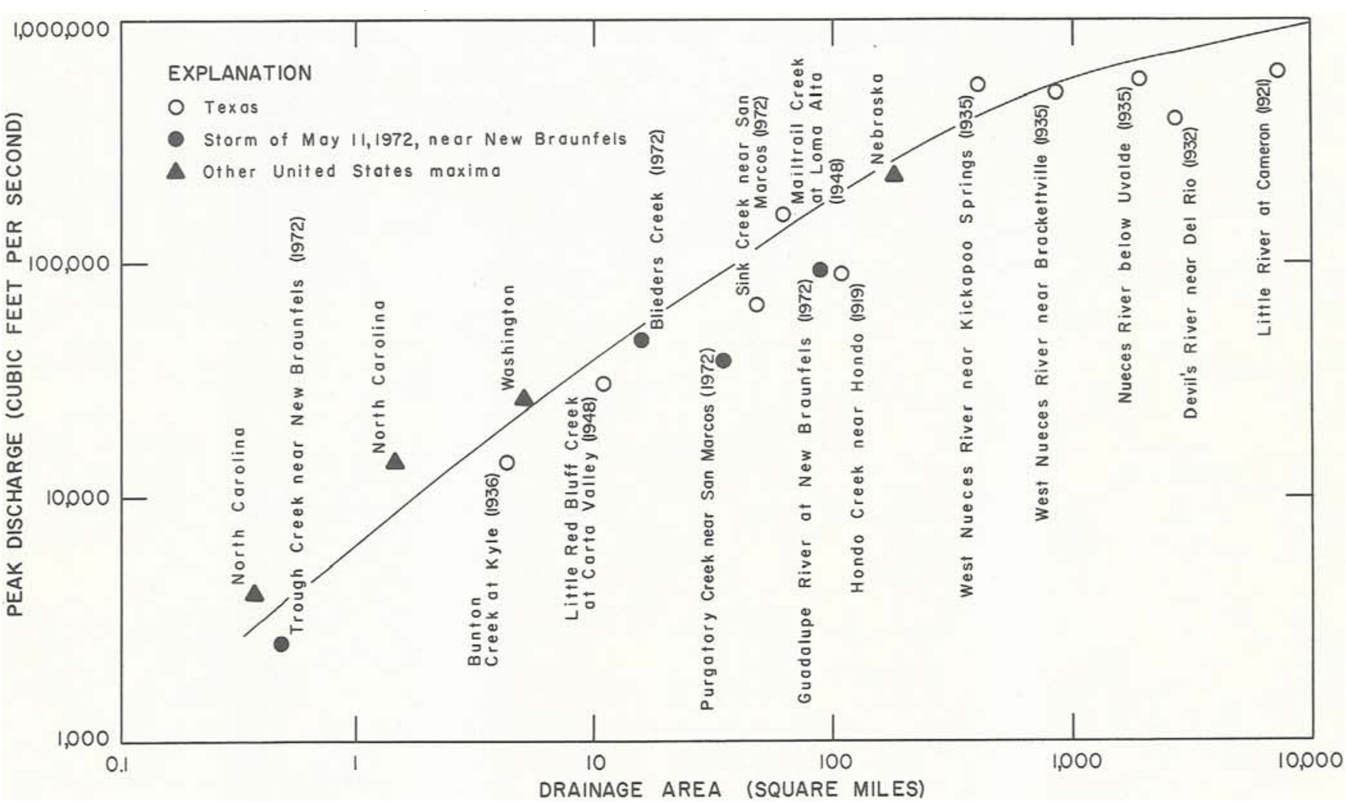

Figure 4. Maximum flood discharges recorded in Central Texas in relation to drainage area. The trend line is a national maximum determined by Hoyt and Langbein (1955).

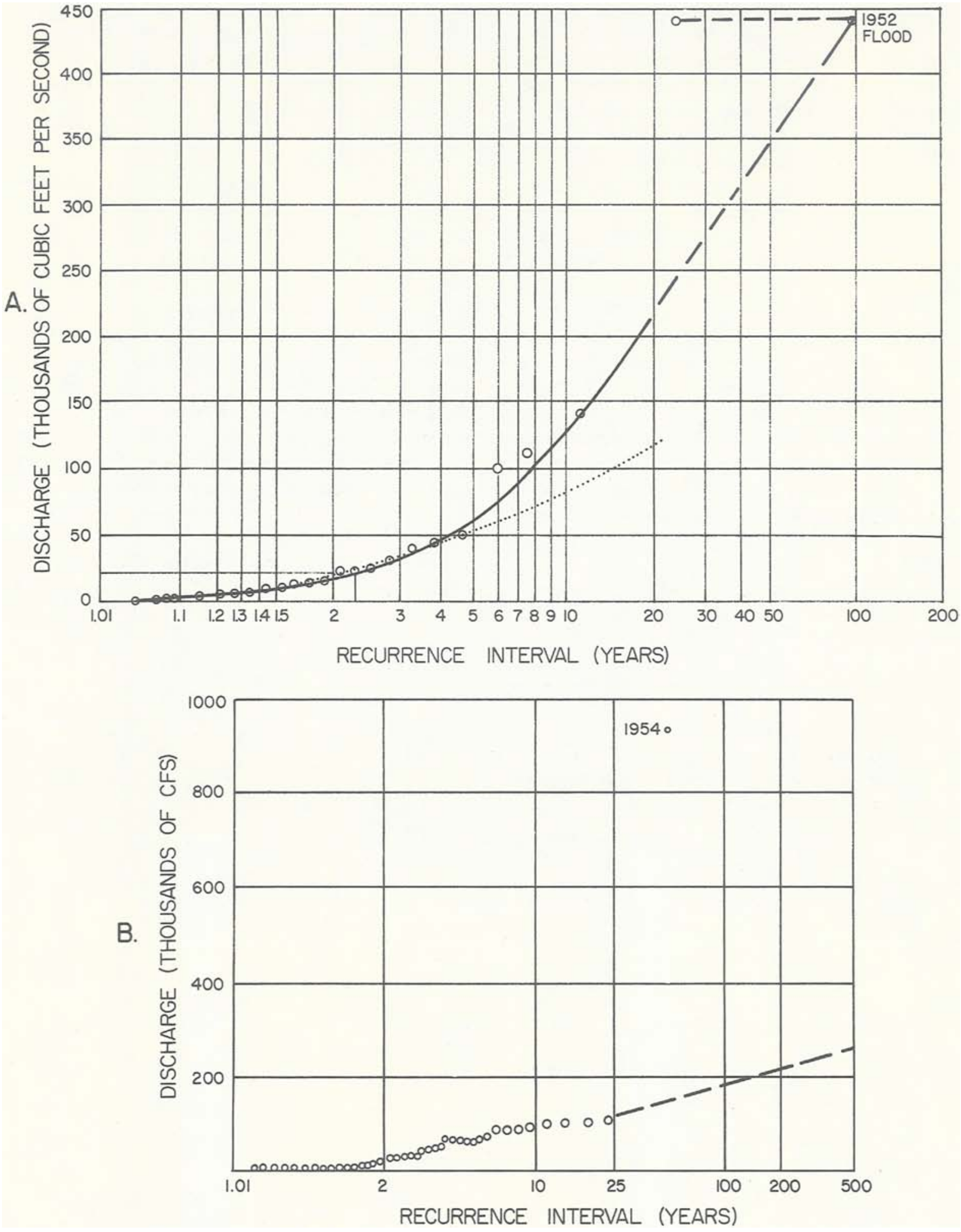

Figure 5. Flood-frequency curves for Central Texas rivers. (A) Annual flood-frequency curve computed from streamflow record of the U. S. Geological Survey gage on the Pedernales River near Johnson City, Texas, 1940-1961. The dotted line shows the trend of data indicated by events with a recurrence interval of less than 5. (B) Maximum annual peak discharge of Pecos River near Comstock, Texas (Myers, 1969). Dashed line shows the trend exclusive of the 1954 flood peak.

show that high-magnitude, low-frequency events may respond to very different meteorological controls than do events of low to moderate frequency which appear in streamflow records. The only means to analyze such catastrophic events is to either (1) transpose the maximum storms that have occurred somewhere in the region to the location of interest (Myers, 1969), or (2) extend the flood record into the past by geomorphic-geologic methods.

Perhaps the best way to illustrate the hydrologic character of Central Texas floods is to present a detailed analysis of a single flood. Around 8:00 p.m. on May 11, 1972, a series of intense thunderstorms formed southwest of New Braunfels, Texas, and moved northeastward along the Balcones Escarpment. The isohyetal map (fig. 6), developed by Colwick and others (1973), shows that the center of the storm had about 16 inches of rainfall. Reports from local residents indicated that the storm only lasted 4 hours and spread an average of perhaps 8 inches over 300 square miles. Fragmentary evidence of the time distribution of the rainfall indicates that nearly 75 percent fell during the most intense hour, between 8:40 and 9:40 p.m. on May 11, 1972.

The stream gage on the Comal River recorded much of the storm runoff (fig. 7). Some of the most intense rain fell on the catchment of Blieders Creek, a tributary to the Comal River. Blieders Creek was the closest of the streams contributing runoff from the Balcones Escarpment to the stream gage. The gage recorded the passage of the flood crest from Blieders Creek at 11:45 p.m. on May 11. This represents a lag time of approximately 3 hours between the

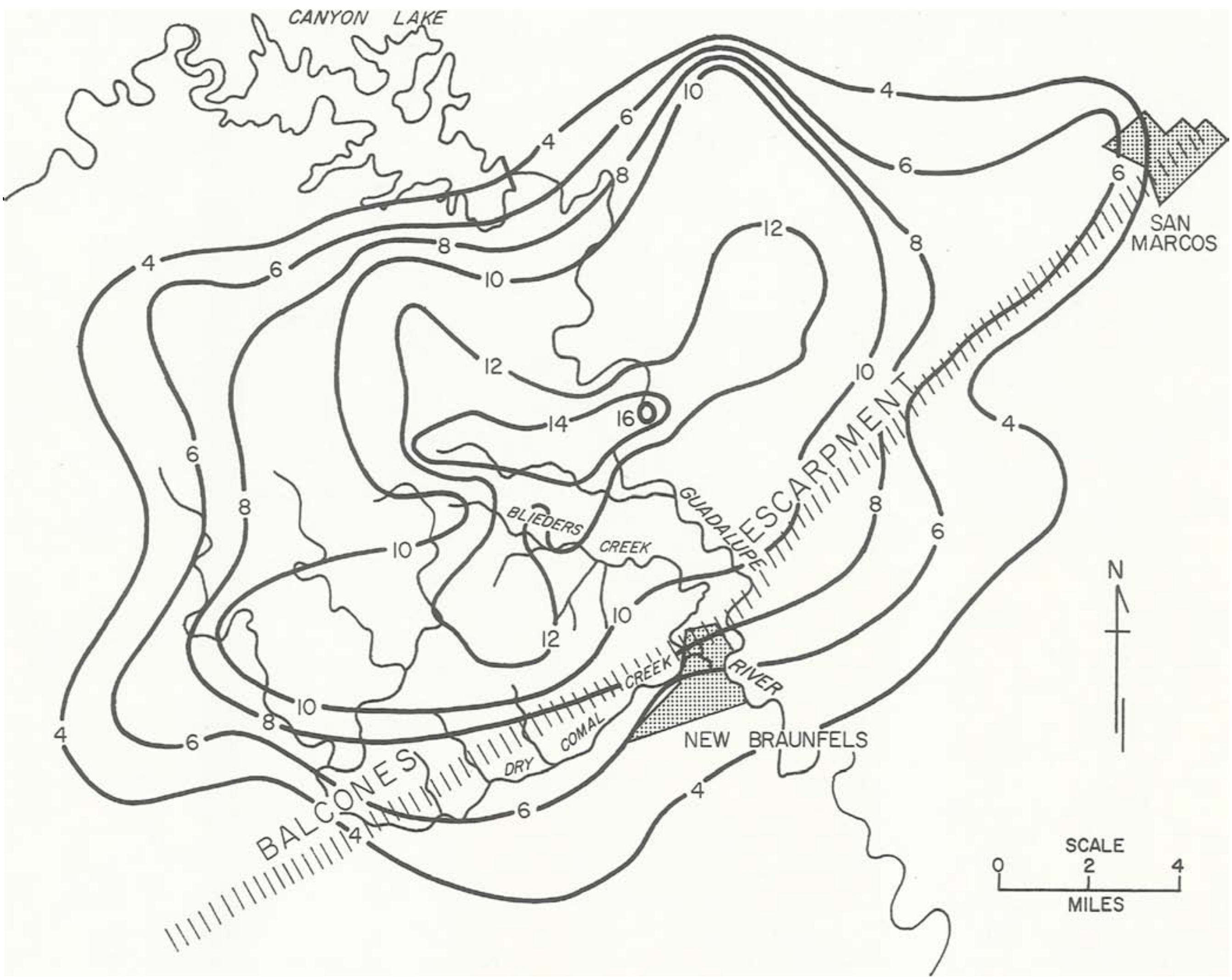

Figure 6. Location map and isohyetal map for the storm of May 11, 1972. Contours represent inches of rainfall recorded by the Soil Conservation Service "bucket survey" in a 4-hour period (Colwick and others, 1973).

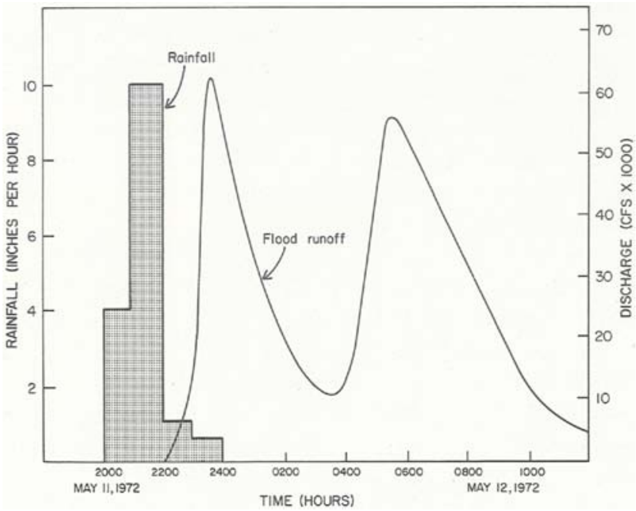

Figure 7. Rainfall and runoff for Comal River at New Braunfels, Texas, flood of May 11-12, 1972. Rainfall distribution assumes that 16-inch recorded maximum was time-distributed according to a unit distribution of storm rainfall recorded at Canyon Dam (Colwick and others, 1973). Runoff was computed by the U. S. Geological Survey from visual observations of water surface elevations at regular time intervals.

centers of mass for the rainfall distribution and for the flood hydrograph, respectively. The crest rose 7.5 feet in 15 minutes and 30 feet in 1 hour 45 minutes. The second peak on figure 7 was caused by runoff that followed the longer flow path along Dry Comal Creek to the stream gage. That crest was delayed until 5:30 a.m. on May 12.

Flooding along the Guadalupe River resulted from runoff in the 86 square miles of drainage downstream from Canyon Dam. Although Canyon Dam protects New Braunfels from runoff derived in 1,432 square miles of upstream drainage, it had no effect on the May 11 storm, which was situated along the Balcones Front downstream from the dam. The Guadalupe River rose 12.5 feet in 30 minutes and 28 feet in 2 hours. The maximum discharge was 92,000 cfs at 12:30 a.m. on May 12. The recurrence interval for such an event is very difficult to estimate. Colwick and others (1973) note that the 16 inches of maximum point rainfall in 4 hours is 2.5 times that of the 4-hour, 100-year-frequency rainfall (U. S. Weather Bureau, 1961). A flood-frequency analysis for the Guadalupe River at New Braunfels by the Log-Pearson Type III method (E. V. Diniz, written communication, 1973) suggests that the flood represents perhaps a 40-year recurrence interval for the entire 1,518 square miles of drainage above the gage. For the 130-square-mile basin of the Comal River, the Blieders Creek flood peak is approximately a 70-year frequency. The difficulties with such numbers is underscored by the fact that the Guadalupe flooding was produced entirely by runoff from only 86 square miles and the Comal River peak was largely produced by runoff from the 15-square-mile catchment of Blieders Creek.

SOME GEOMORPHIC EFFECTS OF CENTRAL TEXAS FLOODS

A reconnaissance study of flood scour and deposition for the 1972 New Braunfels flood has revealed spectacular effects along Blieders Creek. Prior to the thunderstorm cloudburst, the valley floor was mostly covered by an organic soil and turf layer 6 to 10 inches thick that had developed on coarse stream gravels marginal to the low-flow channel. Low brush, scrub oak, and large deciduous trees characterized the channelway (fig. 8A). The estimated peak flood discharge of 48,400 cfs for the 15-square-mile catchment area resulted in widespread devastation to the vegetation and soil cover. The combination of scour and coarse cobble and boulder deposition created a bare valley bottom exposing white limestone bedrock and fresh alluvium (fig. 8B). Preflood and postflood channel cross sections (fig. 9) show that scour occurred in the deeper portions of the channel, probably at mean flow velocities of 6 to 10 fps. Deposition of gravel berms similar to those observed by Scott and Gravlee (1968) occurred along the channel margin. Pebble counts revealed that the mean intermediate diameter of the deposited bedload was 1 to 2 inches. Boulders as large as 4 x 4 x 3 feet were transported for short distances by the flood flows.

Flood effects were particularly pronounced at meander loops. On the inside of one bend (fig. 10), a chute 250 feet long, 35 feet wide, and up to 6 feet deep was scoured in coarse channel gravels. Sediment scoured from the chute was deposited as a large bar immediately downstream. Longitudinal bars of gravel and elongate scour holes occur at higher elevations on the inside of the bend. Scour on the inside of meander bends resulting from high flows can be explained alternatively as (1) a morphological response to higher discharge that would require a meandering tendency with longer wavelength (Tinkler, 1971, p. 1787), or (2) increased shear stress that develops on the inside of meander bends during extreme-flood stage (Baker, 1974, p. 139).

In contrast to the spectacular effects observed along Blieders Creek, very little geomorphic change was observed along the Guadalupe River as a result of the 1972 flooding. The Guadalupe is a relatively large river with a channel that has adjusted to the flow contributed from its drainage basin of approximately 1,518 square miles. Its gradient is

(U.S.D.A. Photo BQu-2v-161, 2-1-58)

(Courtesy of New Braunfels Herald)

Figure 8. Geomorphic effects of the 1972 flood along Blieders Creek. (A) Vertical aerial photograph of Blieders Creek taken in February 1958. The active channel is somewhat obscured by grass and soil. Note the extensive brush and tree vegetation along the stream course. (B) Oblique aerial view of the same reach of Blieders Creek looking east immediately after the 1972 flood. The arrows point to the same meander loop as in (A) above, which is mapped in figure 10.

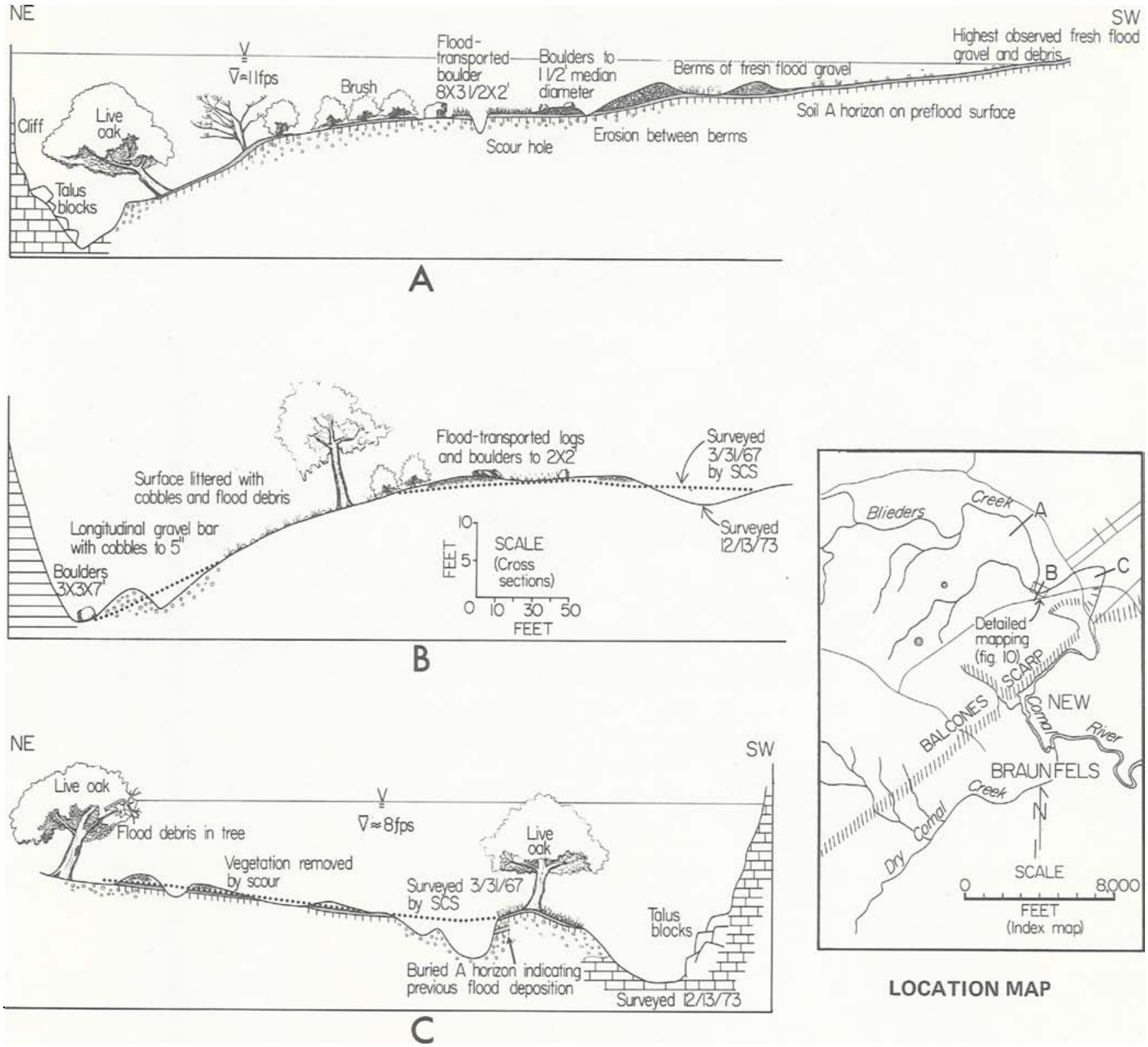

Figure 9. Cross sections of Blieders Creek before and after the flood of May 1972. The preflood sections were surveyed by the Soil Conservation Service on March 31, 1967. The postflood sections were surveyed by P. C. Patton and V. R. Baker in December 1973 and March 1974. Mean flow velocities were determined by dividing the maximum flood discharge (48,400 cfs) by the cross-sectioned area indicated for the maximum flood stage (Stewart and LaMarche, 1967).

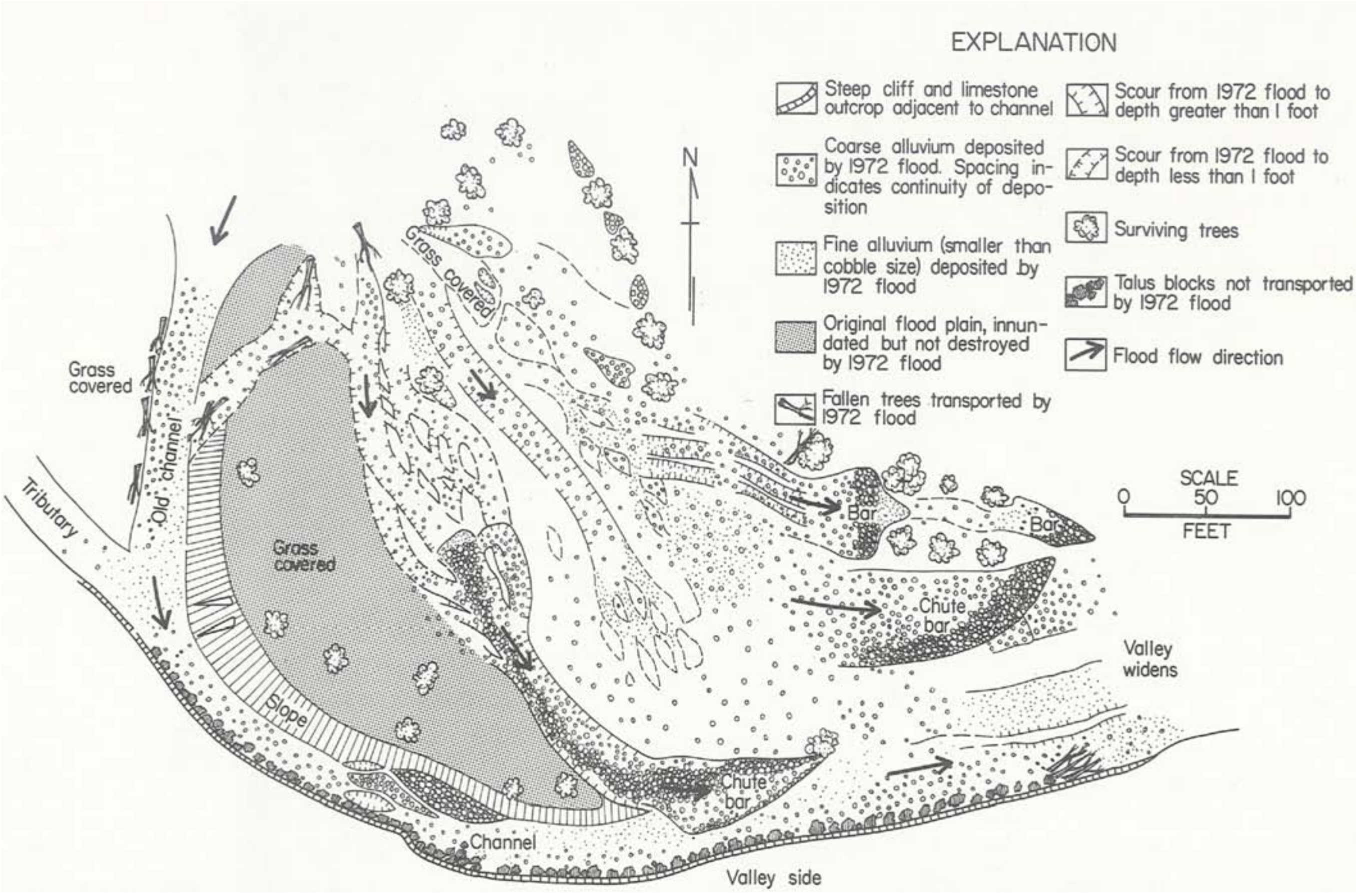

Figure 10. Detailed planetable sketch map of a meander loop of Blieders Creek showing scour and deposition features resulting from the 1972 flood. Prepared by survey with tape and alidade in March 1973. Location of detailed map is shown in figure 9.

approximately 0.0013. For the Guadalupe, the 1972 flood was approximately a 40-year-frequency occurrence (calculated from gaging station records). Blieders Creek, in contrast, is a high-gradient (0.010) stream draining the Balcones Escarpment. It has a drainage area of only 15 square miles. The Blieders Creek erosion was the result of a more catastrophic occurrence on a higher gradient stream.

The Blieders Creek erosion was not modified by subsequent lower discharges, as has been described for the effects of Hurricane Agnes flooding in the humid northeastern United States (Costa, 1974a). The morphology of the rock channel of Blieders Creek appears to be adjusted to relatively infrequent, high-magnitude controlling discharges. Tinkler (1971) suggested that the morphology of Central Texas streams, especially their meander wavelength, was adjusted to flood discharges that have a recurrence interval between 10 and 50 years. This contrasts to alluvial meanders which are adjusted to much more frequent flows, perhaps with recurrence intervals between 1 and 3 years (Carlston, 1965; Dury, 1965).

If the bedrock valley meanders of Central Texas can be related to formative discharges of a known recurrence interval, the bedrock channel morphology of these streams can in itself be used as a predictive hydrologic tool. To test this hypothesis, techniques described by Dury (1958) were used to measure meander wavelength along stream reaches near gaging stations in the Colorado, Guadalupe, San Antonio, and Nueces drainage basins. A relatively good correlation (fig. 11) was obtained between these values and the maximum discharge of record (Patterson, 1963; Ruggles, 1966). Correlations to discharges of calculated recurrence interval (Benson, 1964) were unsatisfactory. The tentative conclusion is that wavelength is adjusted to large, infrequent flows, but that the sporadic flood regime of Central Texas with great variability of storm magnitudes in time and space prevents definite assignments of recurrence intervals.

The narrow bedrock valleys of the Edwards Plateau in the vicinity of the Balcones Escarpment produce constrictions of flood flows that result in large discharges being

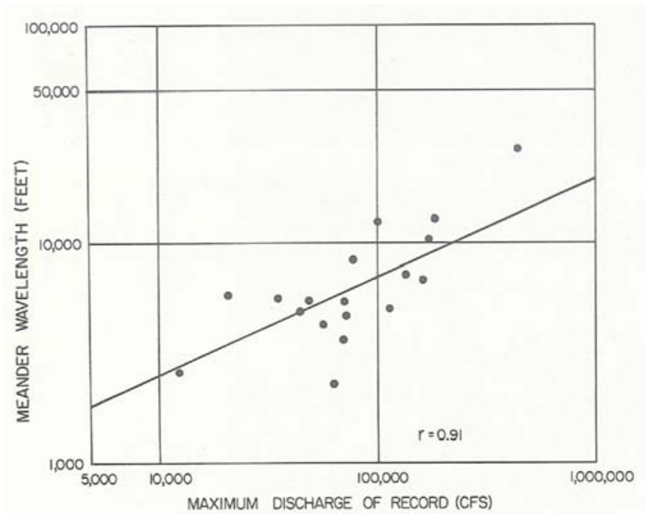

Figure 11. Relationship between meander wavelength and maximum discharge of record for rivers in Central Texas.

accommodated by relatively great flow depths. High flood stages on the major rivers drown the mouths of low-order tributary valleys and result in eddies at tributary junctures. The maximum height of the suspended sediment deposited at such slack-water locations might be used as a measure of the maximum stage achieved by flooding along a particular fluvial reach. Such an approach, also used by Baker (1973), assumes that (1) the slack-water deposits are related to the present regime of the stream, and (2) the stream is not rapidly downcutting. Preliminary field studies indicate that both assumptions can be validated by the study of paleosols associated with the slack-water deposits. Along Cibolo Creek near Bulverde, lateral migration of the active channel is resulting in slack-water deposition above ancient alluvial gravel highly indurated by $CaCO_3$ cementation. The modern channel is cut only 2 feet below the ancient gravel. The slack-water deposits, which occur up to 21 feet above modern river level, show only incipient A-C soil profiles of minimal development. The brownish-black (7.5 YR 3/1) A horizon contains 86 percent sand and 13 percent silt and grades to a relatively uniform dull-brown (7.5 YR 6/3) mixture of 95 percent sand and 5 percent silt. The lack of evidence of textural B horizon development and the presence of only a slight color change that might be attributed to oxidation in the C horizon suggest a very young soil (probably less than 1,000 years old).

At Trammel Crossing on the Pedernales River, the slack-water deposits display alternating 2- to 4-foot-thick units that grade upward from loamy sand (perhaps 20 percent silt-clay) to loam (50 percent silt-clay). These layers probably represent individual flood events during which the sand-rich layer is deposited at rising flood stage and the silt-clay zone is deposited during falling stage. Utilizing the highest such deposits as a measure of maximum flood stage, cross sections were drawn based on field surveys at three locations (table 1). Channel slope was estimated from 7½-minute topographic maps. This information was then used to calculate discharge using the Manning equation. Although the accuracy of such a calculation is subject to many limitations (see Chow, 1959), it is interesting that the resulting discharge determinations were found to be quite close to the maximum floods of record at three locations (table 1).

Table 1. Peak flood discharges along Central Texas streams, determined from studies of flood slack-water deposits

Location	Elevation of Slack-Water Deposit above Stream Level D (feet)	Cross-Sectional Area A (ft^2)	Hydraulic Radius R (feet)	Channel Slope from Topographic Map (ft/ft)	Estimated Roughness n	Calculated Discharge Q^1 (cfs)	Maximum Flood of Record (cfs)
Cibolo Creek near Grosser Ranch	21	2,250	7.5	.0023	.045	14,000	15,700[2]
Guadalupe River approximately 8 miles downstream from Canyon Dam	40	17,000	5.5	.0022	.035	107,000	101,000 (New Braunfels)
Pedernales River at Trammel Crossing	45	25,800	21.1	.0036	.035	507,000	441,000 (Johnson City)

[1]Determined from the expression $Q = A\ (1.5/n)\ R^{2/3}\ S^{1/2}$.

[2]Maximum discharge at Bulverde was 21,000 cfs and was caused by runoff from a drainage area of 198 mi^2. Drainage at Grosser Ranch is adjusted to reflect a drainage area of 150 mi^2.

ALTERNATIVE TECHNIQUES FOR FLOOD HAZARD MAPPING IN CENTRAL TEXAS

The need for flood hazard information has led to a reevaluation of various techniques for flood-plain mapping (Wolman, 1971). The approaches considered in this report will be engineering hydraulic-hydrologic, soils, botanic, and geologic. The engineering hydraulic-hydrologic methods are generally considered to be the most desirable for planning and management purposes in urban areas (Wiitala and others, 1961). However, these methods also tend to be the most expensive, costing as much as $1,000 per mile for delineating flood profiles by backwater curve analysis of large-scale topographic maps (Wolman, 1971, p. 1384). In contrast, the mapping of topographic features or soil associations that may correlate to flood levels could cost as little as $1 to $4 per mile of channel (Wolman, 1971). In the next section of this report, possible trade-offs between cost and accuracy will be discussed. These will be used to determine an appropriate flood hazard mapping technique for regional planning in Central Texas.

HYDRAULIC-HYDROLOGIC METHODS

The U. S. Army Corps of Engineers is the principal agency producing detailed hydraulic flood-plain maps in Texas. The Corps' Flood Plain Information Reports present information on two categories of floods—the Intermediate Regional Flood and the Standard Project Flood. The data required to map these floods (Sutton, 1964) include rainfall records, historical flood data, regional extension of existing gaging station records, cross sections, and engineering profiles of the stream channel. Near San Antonio (U. S. Army Corps of Engineers, 1969) the Intermediate Regional Flood is defined as a flood with an average frequency of occurrence (recurrence interval) of once in 100 years. Its determination involves the extension of existing hydrologic records in both time and space. The Standard Project Flood refers to the discharge that could be expected from the most severe combination of meteorologic and hydrologic conditions considered to be characteristic of a particular region. It is generally calculated as 40 percent to 60 percent of the hypothetical Probable Maximum Flood, determined by hydrometeorological techniques of storm transposition.

Discharge information is transferred to natural stream channels by the step-backwater method (Chow, 1959). The computer programs used to perform the necessary water profile calculations pose many difficulties (Eichert, 1970): (1) the correct water-surface profile is not determined for changes from subcritical to supercritical flow and vice versa, (2) the programs generally neglect the effects of scour and sedimentation, (3) many programs neglect the effects of islands of unflooded land that may persist at flood stage, and (4) the optimum cross sections are often not chosen before programming, thereby requiring manual review of the computation.

Flood-frequency relationships are based on detailed observations at gaging stations and occasional postflood surveys of stages attained by selected floods at nongaged sites. These data must be extended in space because Texas has an average of less than two permanent or long-term gaging stations in each county. The usual method (Benson, 1962a) is to relate flood heights of different return periods to the drainage area and the mean annual flood discharge (a chosen index flood). Patterson (1963) used this method to develop two sets of predictive curves for specific Texas regions of generally uniform flood response. One set relates mean annual floods to floods with recurrence intervals between 1.5 and 50 years. The other curves relate mean annual flood to contributive drainage area. Benson (1964) developed a more complex hydrologic model for the entire southwest, relating flood discharge of various recurrence intervals to a host of parameters, including drainage area, main-channel slope, main-channel length, and average number of thunderstorm days per year. The main criticism of hydrologic regionalization is that it lacks a rational basis and should be supplemented by historical evidence of great floods (Cruff and Rantz, 1964). The assumption that magnitude-frequency relationships will be uniform in arbitrarily defined regions may be valid in the humid eastern United States where rainfall is produced by large air masses and runoff is uniform over great areas (Benson, 1962b; Thomas, 1964). However, semiarid regions are well known as areas of highly variable flood response (Dorroh, 1946). Benson (1964) found that a regional multiple-regression model for predicting peak flood discharges of various return periods in Texas could not explain consistently large deviations from the general pattern in the Balcones fault zone. The deviations were attributed to the occurrence of lift-convective storms associated with the topographic rise that occurs along the fault zone (Benson, 1964, p. D63). Benson added that the erratic chance of storm occurrence in this region led to errors in extrapolating the local flood experience of any one site to the entire region.

The extension through time of hydrologic flood-frequency studies based on a sample of streamflow records at a gaging station is subject to several statistical difficulties. The sample of flood events is assumed to be representative of the unknown real population of floods through time. Too small a sample introduces large sampling errors because of random variations of rainfall in time or geographic area (Slade, 1936; U. S. Water Resources Council, 1967, p. 12; Victorov, 1971). Very large historical floods also pose a problem when they are compared to a frequency line developed from short-term gaging station records (see fig. 8). The recurrence interval of such large events is of great importance, but extrapolation of the frequency line is not the way to determine it. The U. S. Water Resources Council (1967) suggests that such events either be eliminated or serve as a basis of adjustment for the frequency line. These difficulties will be most pronounced in regions like Central Texas where there is great variability in the magnitude of flood events.

SOILS METHOD

Wolman (1971) suggested that locally both soils and topography may correlate with specific flood heights. Coleman (1963) made extensive use of soil characteristics for flood-plain identification and mapping in Virginia. Cain and Beatty (1968) combined pedo-geomorphic, photogrammetric, and hydraulic principles in a study of flood-plain soils in Wisconsin. They found a 99-percent correlation between their method and the actual area covered by a major flood of approximately a 100-year return period along the Mississippi River. Yanggen and others (1966) report on flood-plain zoning based on alluvial soils as noted on soil maps of Buffalo County, Wisconsin. Reckendorf (1973) reviewed these and other soil/flood-plain studies and reported on his own investigations throughout Oregon. He found that influxes of new alluvial sediment and organic matter from recent floods can be distinguished from a developmental sequence of pedogenesis on successively higher flood-plain, bench, and terrace surfaces. The soils technique did an adequate job of delineating areas flooded by the 100-year return period event when individually mapped soils or groups of soils were compared to hydrologic studies of flood frequency. The principal use of the technique was in extending information from points of known gage data or historical flood elevations to other localities characterized by the same soil-geomorphic associations. Reckendorf concluded, however, that a better extrapolation could be obtained by geomorphic mapping of stair-stepped flood-plain surfaces on the basis of "typical flood plain morphologic features."

Detailed soil survey maps of Texas prepared by the Soil Conservation Service provide information on various grades of wetness related to soil permeability or to surface and subsurface drainage conditions. They generally do not show coverage by water during floods of known frequency and elevation. Along the Balcones Escarpment, the Frio clay loam and other variants of the Frio series are flooded by events of moderate frequency (perhaps 4 to 10 years). A detailed soil survey of Waco, Texas (Elder, 1965, p. 31) designated three degrees of hazard, as follows: none, infrequent (overflow about once in 2 years), and very frequent (overflow several times per year). The mapped soil series were not used to designate hazards of moderate to catastrophic magnitude such as the 10- to 100-year flood events.

Costa (1974b) concluded that pedologic recognition of alluvial soils is adequate only for areas flooded by moderate floods with recurrence intervals of less than 50 years. Because of the lack of precision in the soils technique, it would be preferable to utilize soils maps in combination with geologic mapping to delineate flood hazard zones.

BOTANIC METHOD

Everitt (1968) delineated flood-plain boundaries in western North Dakota by a study of cottonwood trees. Distinctions between flood-plain vegetation and upland vegetation have been mapped in Oklahoma and New Jersey by Hefley (1937), Ware and Penfound (1949), and Wistendahl (1958). Such studies are usually considered to be much less precise than those traditionally desired for flood hazard evaluation (Wolman, 1971). Studies of flood damage to vegetation, combined with tree-ring analysis to determine the dates of damage (Brink, 1954; Harrison and Reid, 1967; Helley and LaMarche, 1973; Phipps, 1970; Sigafoos, 1964), can be quite accurate but such studies require great expenditure of time by field investigators trained in botanical ecology.

Regional ecological studies (Blair, 1950; Tharp, 1926) suggest that some zonation of vegetation occurs along the major river valleys of the Edwards Plateau (fig. 12). Most distinctive are baldcypress (*Taxodium distichum*) and pecan (*Carya illinoensis*). Baldcypress is hydrophilic with shallow, abundant roots that require a constant moisture supply, usually by submergence. The species only occupies the low-flow channel banks of streams with a permanent base flow. Lines of dead baldcypress occasionally mark former channels isolated by meander cutoffs. Pecan is a dominant species in the alluvial zones bordering low-flow channels. Pecan is confined to areas of well-drained loamy soils not subject to prolonged flooding, which local residents term "pecan bottoms." At Stonewall, Texas, one such pecan bottom was completely removed from the point bar of a Pedernales River meander by the 1952 flood. Trees and supportive soil were scoured, leaving a flat bedrock surface.

American sycamore (*Platanus occidentalis*), eastern cottonwood (*Populus deltoides*), and black willow (*Salix nigra*) grow in close proximity to stream bottoms, but unlike baldcypress they occur along ephemeral tributaries. The shallow roots of the black willow require a constant moisture supply during the growing season. Unlike the pecan, American sycamore may extend from flat-lying bottomlands up relatively steep slopes where the water supply is sufficiently abundant. The alluvial soil zones, including wetter terraces and well-drained flats on active flood plains, contain pecan, hackberry (*Celtis laevigata*), Spanish oak (*Q. shumardii*), elm (*U. americana*), black walnut (*Juglans nigra*), and large live oaks (*Q. virginiana*). However, not all these species are distinctive. The live oaks extend up nearby limestone ledges, where they mix with Spanish oak, white ash (*Fraxinus americana*), red mulberry (*Morus rubra*), and Texas black walnut (*Juglans microcarpa*). They also occur on the vast limestone interfluves in association with juniper, prickly pear, and mesquite. Black walnut tolerates thinner soils and lower moisture than pecan, while Texas black walnut tolerates even drier complex. Particular combinations of soil conditions and water supply appear to be the dominant controls. Because flooding is not a cause of the zonation, botanical flood studies must be combined with other techniques for flood hazard evaluation.

Studies of flood damage to vegetation along the Pedernales and Guadalupe Rivers have shown the following features: uprooting of trees, downstream bending of saplings and brush, burial of tree trunks with overbank sediment, scour marks in sediment around tree trunks, scars on vegetation exposed to flood flows, and placement of vegetation debris in the crowns of trees or on hillslopes. Debris heights measured in October 1973 indicated flood stages of 24 feet at Trammel Crossing (fig. 12) on the Pedernales and 26 feet at Ammans Crossing on the Guadalupe River. Unfortunately, decay, slopewash, and other processes remove such evidence too quickly for this

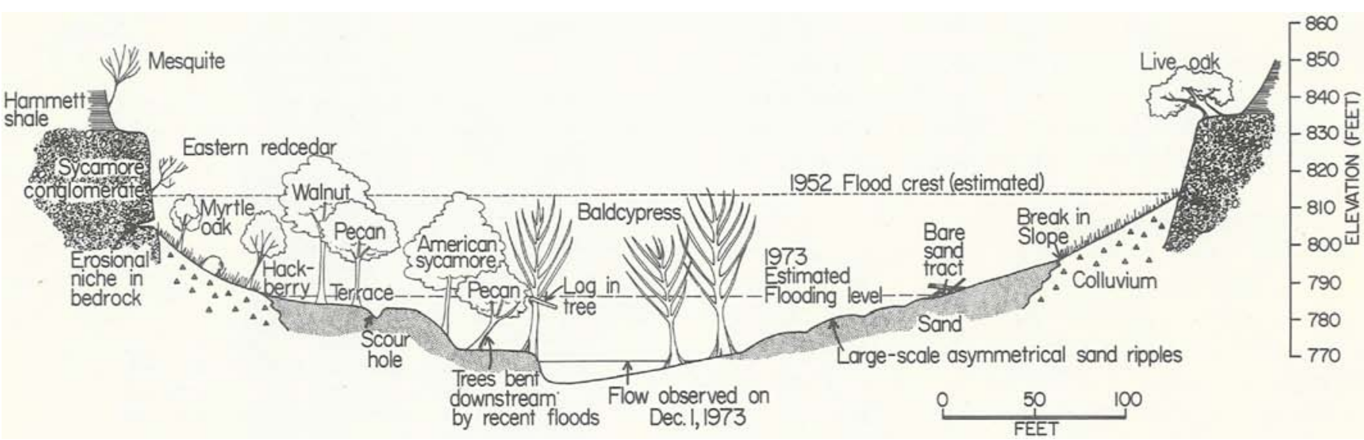

Figure 12. Schematic cross section of Pedernales River valley at Trammel Crossing, Pedernales Falls State Park. Vegetation associations and geomorphic features based on field observations by V. R. Baker, P. C. Patton, and P. A. Smith.

habitats, such as the limestone ledges adjacent to bedrock streams. Spanish oak, in contrast, remains in the well-drained soils of alluvial terraces and colluvium near active streams.

Preliminary biologic assemblage mapping by the Bureau of Economic Geology (Wermund and Waddell, 1974) has shown that the bottomland cypress-pecan assemblage can be easily recognized in the process of environmental geologic mapping from aerial photography. However, the factors which control the zonation of vegetation on Texas river-bottom environments are quite method to be applied to the calculation of less probable flood magnitudes.

GEOLOGIC METHOD

Geologic techniques for flood-plain mapping should not be confused with simple physiographic correlation of specific topographic features with flood discharges of known frequency (e.g., Kilpatrick and Barnes, 1964; Woodyer, 1968). They involve the more extensive investigation of morphology, sedimentology, distinctive erosional features, time sequences of channel abandonment, and compilation of existing pedologic, botanic, and hydrologic information. This concept is similar to Reckendorf's (1973) "combination method" for the construction of flood-plain maps in Oregon. Reckendorf developed a base map by mapping typical geomorphic flood-plain features (see Fisk, 1944; Jahns, 1947; Lueder, 1959) and associated terraces from aerial photography and selected field studies. The available soils, vegetation, historical flood, and hydrologic-hydraulic information can then be superimposed on the geomorphically delineated flood plain. The skilled investigator will use each technique to check and balance the other. Reckendorf found that, in general, there is a strong correlation between geomorphic flood-plain surfaces and river stages for floods of particular frequencies, especially the 100-year average recurrence interval event.

The Bureau of Economic Geology is mapping flood-prone areas on aerial photographs using geologic criteria (Dickerson, 1974) as part of a general program of environmental geological mapping in the Edwards Plateau (Wermund and others, 1974) and adjacent inner Coastal Plain (Gustavson and Cannon, 1974). Map units were developed by a combination of physiographic, pedologic, vegetation, and occasional-flood criteria. Flood plains were recognized as relatively high-probability flood-prone areas by the occurrence of point-bar deposits, scoured channels, and visible evidence of recent flooding. Low terraces were interpreted as low-probability flood-prone areas. Generally, such areas have no visible flood evidence but occur at relatively low levels immediately above active flood plains. Higher terrace levels subject only to catastrophic flooding are also mapped. This mapping program has not sought to associate the delineation of flood-prone areas with specific probabilities of occurrence. However, comparisons of Standard Project Flood mapping by the Corps of Engineers and Bureau of Economic Geology mapping of "low-probability flood-prone areas" have shown close agreement along reaches of Salado Creek, San Marcos River, and Blanco River (Morton, 1974). The principal advantage of environmental mapping is that it is relatively rapid and inexpensive. Its benefits are therefore maximized for small communities, subdivisions, resorts, and rural regions that cannot afford the more expensive engineering hydrologic studies used in larger cities (Dickerson, 1974).

The geologic approach to flood hazard delineation (table 2) should include inventories of historical flood marks on the ground surface, aerial photographs of actual flood events, and local interpretations of existing stream-gaging data. It should also be a subjective appraisal of all existing physiographic, botanic, pedologic, occasional-flood, and regional hydrologic studies to be done by skilled scientists as a part of a regional environmental inventory.

Table 2. Elements of an interdisciplinary geologic flood hazard inventory

DISCIPLINE	SOURCE OF MAPPING DATA
Geology	Aerial photographic mapping of flood-plain features (Fisk, 1944; Jahns, 1947; Lueder, 1959; Reckendorf, 1973) including the following: (1) Active channel and channel bars (2) Point bars (3) Meander scrolls (4) Oxbows and oxbow lakes (5) Sloughs (6) Natural levees (7) Backswamp deposits (8) Sand splays (9) Abandoned channels (10) Flood-plain scarps (11) Chutes and chute bars (12) Terraces and ancient alluvial surfaces now undergoing dissection Field surveys of scour and deposition from past floods: (1) Flood berms (Scott and Gravlee, 1968) (2) Bedforms relict from recent flooding (Williams, 1970) (3) Slack-water deposition at tributary junctions (4) High-water marks from recent floods
Soils	Published detailed soil surveys Preliminary soils mapping available from local Soil Conservation Service offices
Botany and Ecology	Publications and files of the Texas Parks and Wildlife Department and the U. S. Department of Agriculture, Soil Conservation Service Aerial photographic interpretation of tree and shrub assemblages. Recognition of tree crowns from textural patterns on aerial photographs Field surveys of flood damage to vegetation
Engineering: Historical Flood Information	Photography of historic floods High-water marks recorded by Federal, state, and local agencies (U. S. Army Corps of Engineers; U. S. Geological Survey; Soil Conservation Service; Texas Water Development Board; city and county public works and planning departments; conservancy, irrigation, and water control districts; public utilities and large private industrial concerns)
Hydrology	Flood risk reports of the U. S. Army Corps of Engineers, U. S. Geological Survey, Soil Conservation Service, and private engineering consulting firms Regional hydrologic studies (Breeding, 1948a, 1948b; Breeding and Dalrymple, 1944; Breeding and Montgomery, 1954; Patterson, 1963, 1965; Ruggles, 1966; Schroeder, 1973; Texas Board of Water Engineers, 1957)

FLOOD-PLAIN MANAGEMENT

Goddard (1969, p. 12) defines flood-plain management as follows: "all measures for planning and action which are needed to determine, implement, revise, and update comprehensive plans for the wise use of flood plain lands and their related water resources for the welfare of our nation." A flood-plain management program involves eight basic steps (Dougal, 1969, p. 56):

1. Recognition of the flood hazard
2. Flood forecasting and warning systems
3. Flood fighting and emergency measures
4. Adjustments in structures and occupancy in flood hazard areas
5. Flood-plain regulations
6. Land use planning
7. Flood control by engineering structures
8. Permanent maintenance of the flood-plain management program

This report has concentrated on discussing alternative approaches toward achieving step 1. To be truly effective, however, flood hazard information must be brought to the local level of government and then it must serve as a basis for flood-plain regulation, land use planning, and flood control by various levels of government.

LOCAL FLOOD RISK REPORTS

Ideally, every community, county, or local governmental agency should have flood hazard information that includes as a minimum the following items (Murphy, 1958):

1. Topographic map of the flood plain
2. Profiles and cross sections of the river showing river bottom, banks, and flood levels
3. Flood-frequency curve
4. Information on areal extent for the largest flood of record
5. Hydrographs of past major floods
6. Data on monetary extent and type of past flood damage

The U. S. Geological Survey has done much research to determine how flood information can best be presented on maps (Dalrymple, 1964; Bue, 1967; Ellis, 1969). U. S. Geological Survey Hydrologic Investigation Atlases contain the following information: (1) topographic base showing the area inundated by a particular flood, (2) flood-frequency curve, (3) flood profiles, and (4) photographs and descriptions of historic floods. Excellent examples of the techniques required to provide such information to Chicago and Pittsburgh are given respectively by Sheaffer and others (1970) and Wiitala and others (1961). Unfortunately extensive mapping in nonurban areas using their approach is expensive (Dickerson, 1974).

Texas communities which require detailed flood risk reports can obtain assistance by contacting the Texas Water Development Board. The Fort Worth District Corps of Engineers will receive and review applications for flood-plain information studies, as authorized by section 206 of the Flood Control Act, approved July 14, 1960, as Public Law 86-645. The national program (Stephenson, 1969) includes the preparation of flood-plain information reports and the provision of technical services to state and local governments to aid in their preparation of flood-plain regulations. The Corps of Engineers is increasing its use of nonstructural measures in the solution of flood problems.

FLOOD-PLAIN REGULATION

"Regulation" implies restrictions placed by legislative bodies on private and public land uses in flood-prone areas (Liebman, 1973). The following regulation techniques can be used to control land use on flood plains (Murphy, 1958): (1) state laws (statutes), (2) zoning ordinances, (3) subdivision regulations, (4) building codes, (5) urban renewal, (6) permanent evacuation, (7) government acquisition, (8) building financing and tax assessments, (9) warning signs and notices, and (10) flood insurance. Techniques (2), (3), and (4) would primarily apply at the local level, although the real power of local governments to zone is delegated from a state legislature or constitutional provision (Liebman, 1973). Because these regulation techniques are the most effective but are only rarely used, the Water Resources Council recommended model statutes for conjunctive state-local regulation of flood hazard areas. A single state agency, working closely with local governmental units, to gather flood information, delineate flood hazard areas, and aid the local units in regulating land use practices was considered to be the ideal technique. Morse (1962) gives a detailed discussion of the role of state governments in promoting the understanding of both the flood problems themselves and the necessity for land use regulation in their solution. In spite of much legal evidence supporting the use of zoning by state governments to regulate land use on flood plains (Hogan, 1963), these powers have rarely been used.

FLOOD INSURANCE

The National Flood Insurance Act (Public Law 90-448, Title XII, August 1, 1968) authorized the Department of Housing and Urban Development to establish and carry out a flood insurance program. Individuals in Texas can obtain this insurance, but only after their local governmental body has adopted a flood management program that meets criteria developed by the Secretary of Housing and Urban Development. This program must include land use plans, control measures, subdivision planning, and building and health code requirements. In 1969, the Texas Legislature enacted the Texas Flood Control and Insurance Act (Article 8280-3) enabling Texas to participate in the national flood insurance program and naming the Texas Water Development Board as the coordinating agency at the state level (Gillett, 1974).

The National Flood Insurance Program was modified by the Flood Disaster Act of 1973 (Public Law 93-234, December 31, 1973). The new law provides incentives for faster progress, including increases in limits of insurance coverage, provisions for more rapid identification of flood-prone areas, requirements for state and local flood-plain ordinances as a condition of Federal assistance, and requirements for purchase of flood insurance by any property owners who are being assisted by other Federal programs. The task of preliminary delineation of flood plains in Texas is being accomplished with the assistance of the U. S. Geological Survey. These preliminary maps identify special hazard areas (any area with a 1-percent annual chance of flooding) on 7½-minute quadrangles. The special hazard maps are supplied by the Federal Insurance Administrator to assist local communities with the development of local flood-plain management programs. Maps can also be obtained from the Flood Plain Management Branch, Texas Water Development Board.

To qualify for flood insurance, local communities (at least 20 structures) must submit written requests to the Federal Insurance Administrator, HUD. The required study of local floods must be performed by an approved agent, usually the Army Corps of Engineers, Soil Conservation Service, U. S. Geological Survey, or an engineering consultant. The Flood Disaster Act of 1973 allows initial planning on the basis of the emergency program of special hazard mapping. The U. S. Geological Survey technique for special hazard mapping (Kennedy, 1973) involves cross-section measurement from topographic maps, flood-frequency information from the regionalization streamflow records at gaging stations, and computer routing of discharge to determine flood stage. Special hazard maps only identify the 100-year flood plain. The goal was to have 750 such maps completed for Texas by July 1, 1974 (Gillett, 1974). The next step is for local communities to have a detailed rate study, utilizing backwater analysis to precisely identify the 500-, 100-, 25-, and 10-year flood lines. Only residents within the 100-year flood line are required to buy insurance. The 500-year flood line is arbitrarily determined from the envelope of maximum floods (fig. 4). Residents of the 500-year flood plain may purchase insurance if desired. Based on the detailed hydrologic studies, local communities may adopt a variety of acceptable land use plans. Lamesa, Texas, purchased much of its flood hazard zone and turned the land into municipal golf courses.

A sound flood insurance program could solve the nationwide problem of flood damage. However, the existing program has some severe limitations (Hanke, 1973; Liebman, 1973). Flood insurance is not, nor is it likely to be made mandatory for all flood-plain residents; participation is wholly at the discretion of local governmental units.

FLOOD CONTROL

In 1936, Congress passed the Flood Control Act, which held that flood control was (1) a proper function of the Federal government, and (2) justified to save lives and property. Since 1936 the Army Corps of Engineers and the Soil Conservation Service have invested over $7 billion in flood damage reduction measures, mostly engineering works for flood control. By the 1950's, it became apparent that this accelerated program was not reducing flood losses. Today, engineering works are viewed as supplements to overall flood-plain management programs (Dougal, 1969). The types of engineering works used include channel improvements, levees, storage reservoirs, and land management and watershed development. In Texas, the Corps of Engineers is primarily responsible for the first three types and the Soil Conservation Service for the fourth.

Flood control projects can also be divided into those which primarily concern watershed development in upstream areas, and those which concern protection for downstream areas (Leopold and Maddock, 1954). The Soil Conservation Service administers upstream programs in Texas primarily for soil conservation and municipal water supply. Channelways downstream from dams on low-order streams receive flood control benefits only to the extent that small storms introduce heavy rainfall on the drainage areas protected by the control structures. Leopold and Maddock (1954, p. 50) suggested that, as a general principle, small reservoirs on headwater tributaries draining 50 to 125 square miles reduce floods an average of 35 percent. The magnitude of this reduction decreases in a downstream direction. They concluded that such protection is not adequate in terms of replacing downstream protective works.

The Corps of Engineers has the major responsibility in Texas for downstream flood control works, either reservoirs or channel improvements. Corps projects for water resources development require a complex series of steps to determine that a Federal interest exists in such projects (see U. S. Army Corps of Engineers, 1965). Magnitude and frequency relationships must be determined to establish both a design flood against which a given area is to be protected and a maximum probable flood that is the largest flood for which there is any reasonable expectancy in a given climatic region. The maximum probable flood is determined by transposition of hypothetical storms to a position that will give maximum runoff. It frequently is twice the magnitude of a flood with a recurrence interval between 100 and 200 years, i.e., Standard Project Flood (Cochran, 1966). A problem often overlooked by the general public is that there is always a small probability that a flood will occur that is larger than the design flood and which cannot be controlled. This would be particularly significant if the project fostered increased flood-plain development because of a false sense of security. Flood damage from an excessive event would then be greater than would have been the case without the initial degree of protection (Leopold and Maddock, 1954).

"Flood control" is probably a misnomer when applied to engineering works. Dams do not give flood control, but only "a specific amount of flood protection" (Leopold and Maddock, 1954). In Texas this distinction is especially critical. The great potential for truly catastrophic rainstorms makes the possibility of exceeding design floods a very real one that needs to be considered in the protection of life and property. The irregular positioning of major rainstorms relative to existing flood control reservoirs, as illustrated by the 1972 New Braunfels flood, shows that attainment of an adequate degree of protection at all possible locations might require a phenomenal number of reservoirs.

LAND USE PLANNING

One recommendation of the Task Force on Federal Flood Control Policy (U. S. Congress, 1966) was that the Federal Water Resources Council should encourage state agencies to deal with the coordination of flood-plain planning and regulation. A survey of the role of states in guiding land use on flood plains (Morse, 1962) has shown that, like many states, Texas has done a good job in building flood control works. However, continued development in flood-plain areas has caused flood damage potential to increase. Fortunately, Texas has the beginning of an overall statewide water resource program in the Texas Water Plan (Texas Water Development Board, 1968). Flood damage prevention in the Texas Water Plan calls for both flood control measures proposed by the Corps of Engineers and flood-plain management through flood hazard reports and Federal flood-plain insurance.

Effective mitigation of flood dangers will probably have to involve some sort of regulation in addition to structural control measures. However, because flood hazards vary regionally and because flooding is but one of many problems that local communities face, the precise form of regulation needs to vary. One community might find it advantageous to permit flood-plain occupancy, requiring only building adjustments or "flood proofing" (Sheaffer, 1960). Another might have coincident flood hazard areas and open-space needs that would make public acquisition of flood-prone areas attractive. The needs of another community might best be served by the flood insurance program alone. The most effective guidelines for the regional complexity of such approaches would stem from the state rather than the Federal level.

CONCLUSIONS

(1) Spectacular Texas rainstorms and orographic influences combine to produce some of the greatest magnitude floods in the United States. The Balcones Escarpment provides an influence that localizes these events to a broad belt extending from Del Rio, through Uvalde, San Antonio, Austin, Temple, and Waco, to Dallas-Fort Worth. Rainfall of exceptional intensity occurs when an occasional tropical Gulf storm moves inland, and its warm moisture-laden air is cooled by the elevation increase at the escarpment.

(2) Geomorphic studies of bedrock channel morphology, meander wavelength, and flood slack-water deposits offer considerable promise for the estimation of high-magnitude, infrequent discharges in Central Texas because of genetic correlation to the hydrologic maximum flood of record.

(3) Questions of survey expense and time make it desirable to consider alternative approaches to engineering hydraulic-hydrologic methods of flood-plain mapping. Geologic techniques of flood-plain mapping that include a regional inventory of physiographic, pedologic, botanic, and hydrologic information offer considerable promise for relatively rapid, inexpensive flood hazard mapping in Central Texas. The geologic approach is most useful at the regional scale of planning. Local zones of special flood hazards should be studied by more expensive detailed hydraulic-hydrologic methods.

(4) The natural regime of Central Texas rivers involves floods that are highly variable not only in time but also in location. Thus, nonstructural measures, as well as structural flood control devices, should be considered.

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